ICRA 2010 Workshop

Achieving robust, compliant, interactive humanoid robots via active force control

Abstract

A humanoid robot that is capable of working and interacting with humans in our own environment has been a long outstanding goal of robotics research. There has been notable progress using robotic hardware that allows for joint-position control, such as the Honda Asimo and Kawada HRP humanoids. However, due to the limitations of joint-position control, these robots lack sufficient compliance to cope with high uncertainty, or the feedforward control mechanisms that allow for fast, agile, human-like movement. Recent developments in actuator technology have allowed for systems capable of joint-torque control, however, the mechanisms behind these systems vary greatly (including hydraulics, pneumatics, series elastic actuation, etc). The goal of this full day workshop will be to bring together the top researchers in the field to review, compare and contrast leading technologies that allow for active force/torque control of humanoid and legged robots, and additionally compare and contrast the various control techniques that can be applied to these force-controllable systems. Through presentations and discussion panels, we hope to achieve a better understanding of the current state of technology and the directions needed to go in order to progress towards advanced robots capable of compliant, robust, and human-like performance.

Confirmed Speakers

- Aaron Edsinger (Meka Robotics)
- Jonathan Hurst (Oregon State)
- Peter Neuhaus (IHMC)
- Christian Ott (DLR)
- Al Rizzi (Boston Dynamics)
- Taizo Yoshikawa (Honda, Stanford)
- Jonas Buchli (USC)
- Luis Sentis (UT Austin, Stanford)
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ICRA 2010 Workshop on Active Force Control

Title: Series Elastic Actuation for Robotic Arms and Hands
Speaker: Dr Aaron Edsinger
Affiliation: Meka Robotics

Abstract

Robot manipulation has experienced a resurgence of interest in recent years. In particular, many researchers are focused on manipulation in unstructured, human environments where perceptual uncertainty can be significant. Series Elastic Actuator based manipulators are particularly well suited for these settings because of their intrinsic compliance, shock tolerance, robust force feedback, and human safety.

In this talk we will review the implementation of a number of Series Elastic Actuator manipulators and hands, including the MIT Domo humanoid, the Meka A2/H2 arm-hand system, and the HStar RoNA humanoid. We will discuss the advantages and tradeoffs for each design, as well as present directions for future SEA manipulator designs.

We will also present experiments conducted using Series Elastic Actuator based manipulators and demonstrate how the manipulator compliance and force control can often be leveraged to simplify the task solution.

Biography

Dr. Aaron Edsinger is the co-founder of Meka Robotics and its CTO. Dr. Edsinger's expertise is in robot manipulation for human environment and the design of compliant manipulators and hands. At Meka Robotics, he has led development of the world's only commercially available Series Elastic Actuator manipulators and hands. At MIT CSAIL Dr. Edsinger led development of compliant and force controlled upper-torso humanoid robot named Domo. His work has been featured widely in the popular press such as the New York Times, Nature, and the New Scientist. It was selected as a Time Magazine 2007 invention of the year. His on work robot manipulation was selected for the Best Paper Award at the 2006 IEEE Conference on Humanoid Robotics. Dr. Edsinger is the author of numerous publications in assistive and human-centric manipulation, as well as co-founder of the Robotics Science and System Workshop on Robot Manipulation.

Force Control for Spring-Mass Walking and Running

Jonathan Hurst and Devin Koepl

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For robots to approach the performance of animal walking and running, they must be able to attenuate significant disturbances, while maintaining excellent energy economy. Existing passive walkers are capable of energy economy similiar to animals, but they fall in the presence of small disturbances. Robots that rely primarily on active control, such as Boston Dynamics' "BigDog," demonstrate impressive robustness to disturbances at the expense of energy economy [1]. Our goal is to combine the robustness to disturbances of actively controlled machines with the energy economy of a passive dynamic walker.

We propose a novel concept of adding force control to a spring-mass model, by including a motor, as shown in Figure 1. Because existing force control actuators such as the MIT Series Elastic Actuator are schematically similiar to this spring mass model, it is easy to combine the two concepts on a real system[2]. However, in addition to using series elasticity for force control, our model stores energy in its springs. The spring stiffness is tuned to the natural frequency of our desired spring-mass hopper, so the energy will be stored in the spring as the mass decelerates, and recovered as the mass accelerates towards liftoff. In the ideal scenario, the motor does no work, and all of the model's behavior is expressed by the passive dynamics of the system as it bounces up and down. Any disturbance that the model encounters is handled by the actively controlled motor.

Our simulation results, shown in Figure 2, show that active force control can make the spring-mass model robust to ground disturbances with limited sensory input. The controller is based only on the spring deflection, and not on any external sensing, which makes it practical for legged robots that have incomplete knowledge of the world. While the passive dynamics of the system attenuate very high-frequency disturbances, the force controller focuses on the middle-frequency disturbances, leaving any high-level gait choices or stride-to-stride control to a higher-level control system.

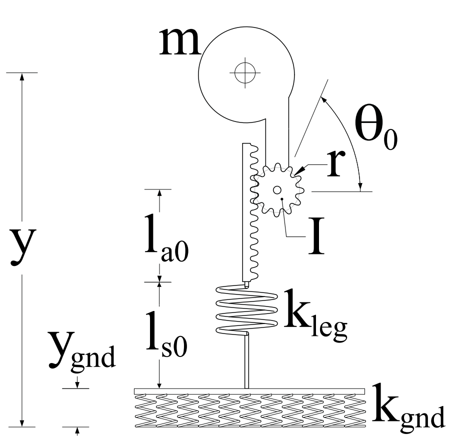


Fig. 1. Force controlled spring-mass model with reflected motor inertia, shown at the instant of leg touchdown on a compliant surface.

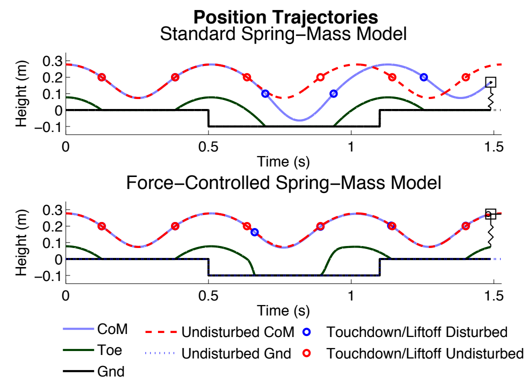


Fig. 2. Comparison between the center of mass trajectories of the standard vertically hopping, spring-mass and force controlled models encountering an unexpected decrease in ground surface. Our force controlled model roughly maintains the center of mass trajectory of the passive undisturbed spring-mass model.

Our motivation for this work is based on observations of animals, which are able to economically walk and run at varying speeds over varying terrain. Because our goal is to build robots that can match the performance, economy, and robustness of animal walking and running, our models incorporate passive dynamics similar to those observed in animal walking and running. In addition to passive dynamics, animals also use active control to compensate for disturbances. For example, guinea fowl are able to accommodate for a drop in ground height by rapidly extending their leg into an unexpected disturbance, as shown in Fig. 3, resulting in only slight deviation from their undisturbed gait [3].

I. CONTROLLER

The active control system in our model intervenes with the passive dynamics only to accommodate ground disturbances. Our controller attempts to match our model's toe force profile to that of an equivalent undisturbed spring-mass model, such that its center of mass movement approximates that of the undisturbed model. When our model encounters an unexpected change in ground height or stiffness, the leg extends or retracts such that the toe forces match those of the

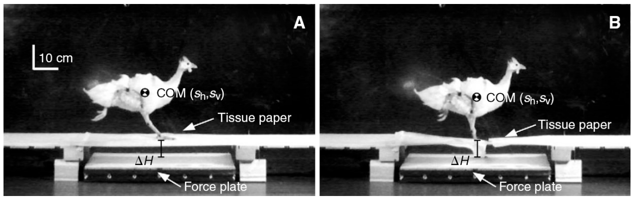


Fig. 3. Motivation comes from the economy and disturbance rejection ability of animals such as the guinea fowl. The guinea fowl is able to accommodate for the unexpected decrease in ground surface without a significant change to its steady-state center of mass motion.

undisturbed passive dynamics. During undisturbed hopping our simulation behaves like a simple spring-mass model without interference from active controllers. Our model's spring exerts all of the work required to decelerate and re-accelerate the system after leg touch down.

II. Example: Ground Height Disturbance

Figure 2 shows the disturbance rejection ability of our force controlled model as compared to the standard spring-mass model in simulation. Unexpected changes in ground height result in a temporary change in hopping height and a permanent shift in hopping phase for the standard spring-mass model, but the simple addition of active force control allows the system to accommodate for ground disturbances and closely follow the toe force profiles and center of mass trajectory of the undisturbed system.

III. CONCLUSIONS AND FUTURE WORK

Active force control combined with a correctly sized leg spring yields good disturbance rejection, while maintaining the energy economy of a completely passive system during steady-state vertical hopping. In the presence of disturbances, we are able to match the toe force profile to that of a passive spring-mass model on a flat rigid surface. Because the toe force profiles are identical, the model's center of mass movement follows that of the ideal passive system.

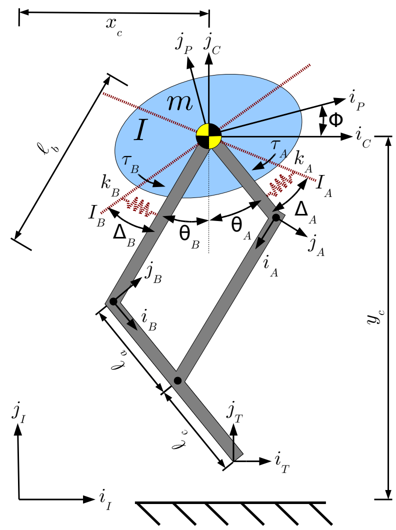
The long-term goal of this work is to build a biped with excellent energy economy capable of robust walking and running gaits. As a step towards this goal, we are extending the single degree of freedom model presented here to a two degree of freedom robot leg shown in Figure 4(b), which will be first tested as a monopod, and eventually be incorporated into a tether-free biped. With these real-world devices based on sound theoretical grounds, we hope to approach the performance of animal walking and running.

References

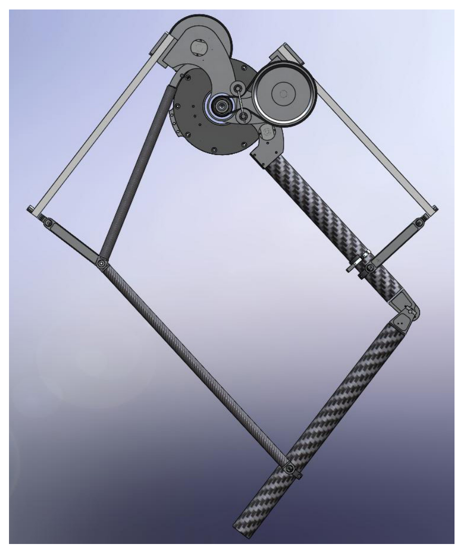
[1] G. N. R. P. Marc Raibert, Kevin Blankespoor and the BigDog Team, "Bigdog, the rough-terrain quaduped robot," April 2008.

[2] G. A. Pratt and M. M. Williamson, "Series elastic actuators," in *IEEE International Conference on Intelligent Robots and Systems*, vol. 1, pp. 399–406, 1995.

[3] M. A. Daley, J. R. Usherwood, G. Felix, and A. A. Biewener, "Running over rough terrain: guinea fowl maintain dynamic stability despite a large unexpected change in substrate height," *The Journal of Experimental Biology*, vol. 209, pp. 171–187, November 2005.



(a) Our proposed robot model, mathematically equivalent to Figure 1, but more closely matching a plausible mechanical instantiation



(b) A recent revision of the mechanical design for ATRIAS, designed specifically to match our mathematical model and interface cleanly with theoretical model-based controllers.

Fig. 4. Our actuated dynamic models are mathematically equivalent to the popular Spring-Loaded Inverted Pendulum model, if the actuators are held stationary and prevented from adding or removing energy from the system. The added actuation introduces dynamic limitations to the mathematical model, such as inertia, that are unavoidable in real systems.

Jonathan Hurst is an Assistant Professor of Mechanical Engineering at Oregon State University. He received the B.S. degree in mechanical engineering, the M.S. in robotics, and the Ph.D. in robotics from Carnegie Mellon University, Pittsburgh, PA, in 2001, 2004 and 2008. His Ph.D. dissertation was entitled ``The Role and Implementation of Compliance in Legged Locomotion.'' Research interests include legged locomotion, natural dynamics, and robot actuation.

Compliant Actuation and Control of the M2V2 Humanoid Robot

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Compliant control is critical for robust and practical legged locomotion in real environments. To date, most humanoid robots have been controlled with rigid high gain tracking of joint trajectories and typically limited to pre-scripted performances. This has limited their applicability to controlled environments with nearly perfect models of the environment and little physical contact with other robots or humans. Before humanoids can be utilized in real world applications they need to be able to safely interact physically with other robots and humans, recover from unforeseen disturbances, and walking over unmodeled terrain.

There is a growing community of researchers working on compliant control, but as with any new community, the results are often difficult to compare. Typically, researchers describe their control algorithm and include a brief descriptive summary of the hardware. Two aspects that are often overlooked are the actuator characteristics and performance metrics. These two aspects are important in leveraging the work of others in the community and to help propel future advances.

We will discuss our current work using these guidelines. First we will present our control algorithm. Then we will discuss our actuators, specifically identifying the issues that affect the performance. We will conclude with a discussion on performance metrics. The hope is that it will spur deeper discussions on these critical areas to allow the compliant control community to better leverage its work.

Compliant Control Algorithm

Our development efforts have focused on compliant control and on bipedal locomotion algorithms that are stable in the presence of external force disturbances and able to handle unmodeled or incorrectly modeled terrain. The first line of defense in being able to stay balanced in the presence of disturbances is having joint-independent stance control. Our approach to controlling the support leg(s) is based on Virtual Model Control, in which virtual components create virtual forces which are then simulated through the application of joint torques. In the case when a single leg, possessing six actuated degrees of freedom, is providing the support for the body, the six forces and torques on the body (the reaction point) can be mapped to the required joint torques. This mapping is performed through a Jacobian transformation based on the positions of the joints. If both legs are on the ground, there is actuation redundancy. This redundancy can be exploited in order to minimize ground shear forces, balance foot load, or a number of other optimizations.

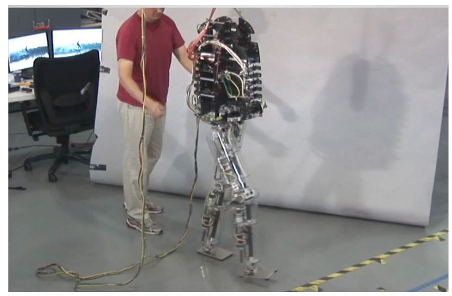

Figure 1: Humanoid Robot M2V2 recovering from a moderate forward push while standing and balancing on one leg. The robot continuously computes the Capture Region. Once the Capture Region no longer intersects the support foot, the robot determines where to step such that the Capture Region will intersect the support polygon once the step is complete.

The benefits of this control technique over rigid position control can be seen in the ability of the robot to handle disturbances while remaining balanced. We have demonstrated this ability on our robot platform, M2V2 (Figure 1**Error! Reference source not found.**), by pushing and pulling on the robot while it is balancing, and by externally raising, lowering, and shifting the ground support while the robot is balancing on two legs. Video, papers, and more information can be found at http://robot.ihmc.us.

If the disturbance is significant enough, then the robot must take a step in order to prevent a fall. To determine if a step is required, we use a simple Linear Inverted Pendulum model to estimate the One-Step Capture Region, the region on the ground in which the Center of Pressure must lie to come to a stop in a single step. If the Capture Region leaves the convex hull of the support polygon, the robot must take a step to prevent a fall. The robot must then step into the Capture Region in order to regain balance in one step.

To approximate the location of a Capture Point, we use the Linear Inverted Pendulum Model. With this model the dynamics are linear and second order. If we write the dynamics in terms of the Capture Point location, then they become first order. The Linear Inverted Pendulum Model assumes a point mass robot walking at a constant height. While this model is a simplification of a real robot, we find that it is adequate for walking and recovering from moderate disturbances.

Moving a foot to the Capture Region requires quickly swinging the swing leg. During leg swing, we currently switch to a high impedance controller such that we can position the leg accurately. Once the leg has made initial contact with the ground, we switch control modes for the leg joints back to low impedance. We are currently looking into more compliant control techniques for quickly and accurately swinging the leg.

In order to implement compliant control techniques such as Virtual Model Control, we utilize Series Elastic Actuators (SEA) at each of the twelve actuated degree of freedom on M2V2.

Force Controllable Actuators

A major limitation in compliance control is the available actuation technology. Compared to human muscle, the available technology for robotic actuators for legged locomotion cannot match performance. The reason that human muscle is such a good actuator is that it can actively adjust its impedance from nearly completely limp to fairly stiff with high damping. Developing force controllable actuation technology is important for high fidelity compliant control.

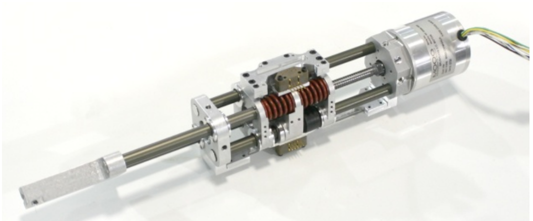

Figure 2: Linear Series Elastic Actuator used in M2V2. There are 12 identical actuators on the robot.

Each Series Elastic Actuator consists of a brushless DC motor which drives a ball screw. The output of the ball screw is connected to a set of die compression springs, which are connected to the output. The linear motion of the output is transferred into rotary motion through either a lever arm or pulley at the joint. The force in the actuator is measured by measuring the compression of the springs. We use linear incremental encoders to measure the spring deflection as well as the output position of the actuator.

Our work on designing a new humanoid robot, as well as our research on robotic exoskeletons has led us to carefully analyze the design of the Series Elastic Actuator. There are several factors that affect the performance of an SEA. These issues include encoder resolution, amplifier and motor saturation, speed limits, transmission and gearing efficiency, spring stiffness, and control loop rates. The selection of the spring stiffness is highly dependent on the other parameters of the actuator. For example, a very stiff spring used in conjunction with a low resolution encoder would result in reduced performance due to low force resolution. However, quantifying the relationships between actuator non-idealities and performance is difficult without a simulation due to the non-linear nature of the non-idealities. In our experience, speed limits of the actuators can be problematic with low spring stiffnesses or high gear ratios.

We use a simulation tool called the Simulation Construction Set, developed by Yobotics, Inc., to evaluate and compare different actuator designs. Because of the significant non-linearities of the actuator, closed-loop performance is difficult to predict without performing a dynamic simulation. We performed a linear analysis of the closed loop system, neglecting amplifier saturation, and could achieve excellent bandwidth on force tracking. However, in simulation, once we applied the current limits, the performance decrease with increase amplitude.

Performance Metrics

It is relatively straightforward to measure and evaluate, and then compare the performance of an actuator. Important measurements include zero motion low-force bandwidth, bandwidth vs. force magnitude, dynamic range, force resolution, and impedance (backdrivability).

It is more difficult to measure and evaluate performance of a compliant humanoid robot. Some easily measured metrics include speed and terrain characteristics, such as step height. Robustness metrics include height of an unknown step down and magnitude of push that can be tolerated without the robot falling.

We believe another useful robustness metric for compliant humanoid robots is the impedance of the robot as viewed from the point of view of the ground as discussed below.

Impedance from Point of View of the Ground

We believe that a humanoid robot should have low impedance as viewed from the point of view of the ground in order to be robust to unmodeled terrain, foot slipping, and disturbances to the stance leg. For instance if the ground were to shift horizontally or vertically or rotate, the robots leg should move with very low resistance force. With a perfectly rigid robot, the impedance of the robot as viewed from the ground would be the entire inertia of the robot. For a compliant robot, the impedance would be much lower. For something like foot angle with respect to a world coordinate system, impedance should be very low since the angle of the foot is not very relevant to the ability to walk and since even small variations in the ground can lead to large variations in foot angle.

Note that in many humanoid robots, even with rigid high-gain actuators, impedance from the point of view of the ground is reduced through different control techniques. One common technique is to change the reference trajectories of the joints to compensate for errors between the measured Center of Pressure and the predicted Zero Moment Point. By changing these reference trajectories fast enough, the robot does present low impedance to foot orientation. In that sense even these stiff trajectory tracking robots are implementing compliant control.

Conclusion

Compliant control of humanoids is important for increasing robustness and operating safely with other robots and humans. Performance metrics are often difficult to define or measure with compliant robots. Low impedance from the point of view of the ground is perhaps one important metric to achieve. Others need to be determined and new actuators and control techniques need to be developed in order to achieve more robust and capable humanoids.

Peter Neuhaus is a Research Scientist at the Florida Institute for Human and Machine Cognition (IHMC) working on legged robotic systems. Neuhaus received his B.S. from MIT and his Ph.D. from U.C. Berkeley. At Berkeley, he worked with Professor Kazerooni, developing the Human Assisted Walking Machine. After receiving his degree, he spent five years in industry. He first started a company called Solo Energy, a micro-turbine company for distributed power generation. He helped the company patent its technology, raise its first two rounds of funding, and build the first two prototypes. After that, he worked for two factory automation companies as a senior engineer and project manager. Some of the projects he managed include a mini-riveting system for one of the largest U.S. airplane manufacturers and a front-end wafer handling system for the semiconductor wafer fabrication industry. At IHMC, Neuhaus' research focus is on robotic exoskeletons for humans and legged-robot locomotion.

He has developed and is currently developing several devices that enhance and person's physical capabilities. Most recently, he led the design, building, and testing of the IHMC Mobility Assist Exoskeleton. By utilizing a custom designed rotary series elastic actuator, this lower extremity exoskeleton gives able-bodied people increased strength or assists a paralyzed person in walking. The IHMC Mobility Assist Exoskeleton is undergoing a full redesign for improve performance and better user fit. Participant testing will resume in the spring of 2010. Two other assist devices that he developed preliminary prototypes for are an underwater exoskeleton for swimming, which allows a person to be able to swim faster and farther with less effort and a powered climbing suit, which enables a person to naturally climb vertically with less effort.

Finally, Neuhaus is actively involved bipedal and quadrupedal robot locomotion. As part of the DARPA Learning Locomotion program, he developed quadrupedal locomotion algorithms for the LittleDog robot. Some of the algorithms include dynamic maneuvers, reactive control, and the Xgait. He is currently working on bipedal locomotion algorithms that are robust to disturbances and unknown terrain. These algorithms will be applied to the IHMC M2V2 force controllable bipedal robot.

Torque feedback based impedance control: Theory, performance, and comparison with admittance control

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***Abstract*— This talk covers three aspects of impedance control for humanoid robots. First a framework for torque feedback based impedance control is presented. The theoretical basis as well as practical design issues are discussed. Secondly, the torque feedback based impedance control concept is compared to admittance control based on end-effector force/torque measurement. Advantages and limitations of both approaches will be discussed. Additionally, a novel concept of a unified impedance/admittance controller is presented. The material of the talk will be exemplified by several applications including two-handed manipulation tasks performed with the DLR's humanoid upper body robot Justin.**

OVERVIEW

Many modern control approaches for robot manipulators assume that the joint torque can be directly commanded via the motors of the robot's joints. In this way, underlying actuator dynamics is neglected. In practice, the performance and sensitivity of these controllers is often affected heavily by friction and flexibility in the drive units. Joint level torque sensing and control is an effective countermeasure against these problems as has successfully been demonstrated, e.g., in the DLR light weight robots [1], [2] and the Sarcos humanoid robot [3].

In this talk, we discuss how inner loop torque sensing can be incorporated in a passivity based control framework for impedance control ([4], [5],Fig. 1). We highlight the robustness and performance properties of this control approach and show several practical applications.

Additionally, we give a comparison of torque feedback based impedance control with state of the art admittance based controllers. For admittance based control, in particular the consequences of using force/torque sensors which are not located at the relevant point of interaction, but at the base, are discussed. It is shown that the force measurement at the base poses some limitations on the achievable impedance dynamics.

In addition to the comparison of impedance and admittance based approaches, we present an overview of a novel control approach, in which the benefits of impedance and admittance based design approaches are combined [6]. Rather than using a controller with fixed causality, the proposed framework incorporates classical impedance and admittance control as two extreme cases of one hybrid controller.

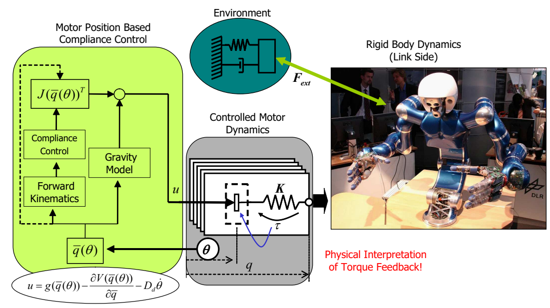

Fig. 1. Passivity based control framework for torque controlled robots.

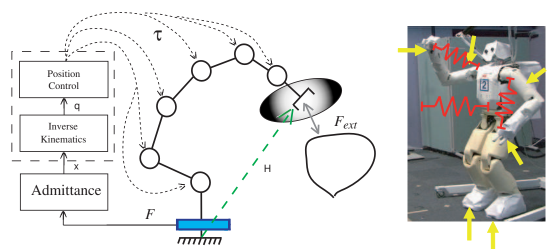

Fig. 2. Admittance Control using a base force/torque sensor.

REFERENCES

[1] G. Hirzinger, N. Sporer, A. Albu-Schäffer, M. Hähnle, R. Krenn, A. Pascucci, and M. Schedl, "DLR's torque-controlled light weight robot III - are we reaching the technological limits now?" in *IEEE International Conference on Robotics and Automation*, 2002, pp. 1710–1716.

[2] Ch. Ott, O. Eiberger, W. Friedl, B. Bäuml, U. Hillenbrand, Ch. Borst, A. Albu-Schäffer, B. Brunner, H. Hirschmüller, S. Kielhöfer, R. Konietschke, M. Suppa, T. Wimböck, F. Zacharias, and G. Hirzinger, "A humanoid two-arm system for dexterous manipulation," in *IEEE-RAS International Conference on Humanoid Robots*, 2006, pp. 276–283.

[3] G. Cheng, S.-H. Hyon, J. Morimoto, A. Ude, G. Colvin, W. Scroggin, and S. C. Jacobsen, "Cb: A humanoid research platform for exploring neuroscience," in *HUMANOIDS*, 2006.

[4] C. Ott, A. Albu-Schäffer, A. Kugi, and G. Hirzinger, "On the passivity based impedance control of flexible joint robots," *IEEE Transactions on Robotics*, vol. 24, no. 2, pp. 416–429, 2008.

[5] A. Albu-Schäffer, Ch. Ott, and G. Hirzinger, "A unified passivity-based control framework for position, torque and impedance control of flexible joint robots," *The International Journal of Robotics Research*, vol. 26, no. 1, pp. 23–39, January 2007.

[6] C. Ott, R. Mukherjee, and Y. Nakamura, "Unified impedance and admittance control," in *IEEE International Conference on Robotics and Automation*, 2010.

Christian Ott

Christian Ott received his Dipl.-Ing. degree in Mechatronics from the Johannes Kepler University (JKU), Linz, Austria, in 2001 and his Ph.D. (Dr.-Ing.) degree from Saarland University, Saarbrücken, Germany, in 2005. From 2001 to 2006 he worked as a PhD student and from 2006 to April 2007 as a postdoctoral researcher at the German Aerospace Center (DLR e.V.) in the Institute of Robotics and Mechatronics. From May 2007 to May 2009 he worked as a Project Assistant Professor in the Department of Mechano-Informatics at the University of Tokyo, Japan. Since June 2009, he is with the Institute of Robotics and Mechatronics, German Aerospace Center. His research interests include nonlinear control of robotic systems, flexible joint robots, impedance control, physical human-robot interaction, and control of humanoid robots.

Alfred Rizzi

At their core every robot control strategy capable of performing useful work mediates the forces that it produces. In this overview I will begin by reviewing the strategies that have been developed to accomplish this goal and explore their similarities and differences. This discussion will be grounded by looking at the role of force control in the implementation of legged robots. Specifically I will draw examples from the variety of legged robots that I have participated in the development of over the past ten years. These include: BigDog, a quadruped robot that can walk, run, balance, climb, carry loads, resist kicks and negotiate rough terrain dynamically; RiSE, a hexapedal climbing robot capable of climbing a variety of natural and man-made surfaces by utilizing generic mechanical adhesion technology; and Petman, an anthropomorphic biped capable of producing natural dynamic walking behaviors. Beyond reviewing the role of force control in these systems, I will also explore issues related to systems engineering, experimental evaluation, and performance.

Bio:
Dr. Alfred Rizzi is the Lead Robotics Scientist at Boston Dynamics. He is responsible for real-time embedded software development and is an expert in robot control, distributed systems and system integration. Prior to joining Boston Dynamics, in 2006, he was an Associate Research Professor in the Robotics Institute at Carnegie Mellon University where he directed research projects focused on hybrid sensor-based control of complex and distributed dynamical systems. Highlights of these projects include the development of embedded software systems and automated behaviors for novel legged mobile robots (RiSE and RHex). Dr. Rizzi received the Sc.B, degree in electrical engineering from the Massachusetts Institute of Technology in 1986. He received the M.S. and Ph.D. from Yale University in 1990 and 1994 respectively. Dr. Rizzi is a co-recipient of the Nakamura Prize for best paper at the International Symposium on Intelligent Robots and Systems in 2001.

An Approach for Multi-Contact and Whole-Body Control of Humanoid Robot

Taizo Yoshikawa

ABSTRACT

Humanoid robots are supposed to coexist with human and work in our daily environment. They can be used to assist and communicate with us in our homes, offices, public spaces, hospitals, disaster areas, etc. When the robot coexists with us in the same environment, safety is one of the most important key problems. Multiple contact or unpredictable contact with the environment or with human may happen in the actual environment. If these contacts are not modeled in the motion controller of the robot, it causes instability of balance and motion control when unpredictable contacts happen while moving in the environment. It causes the critical collision with between the robot and the environment or between the robot and human. In this point of view, compliant and robust contact and motion control is related with safety when the robot moves in the environment.

Honda started humanoid robot project in 1986 to design a robot that can duplicate the complexities of human motion and can genuinely help people. It took more than two decades of persistent study, research, and trial and error before Honda achieved the dream of creating an advanced humanoid robot. The robot can push a cart, open a door, execute human-like gesture, or carrying a tray with stable balancing and walking controller.

So far, the position control system has been applied to most of the humanoid robots and the contact between the robot and the external environment has been limited only through the end-effector of the robot. Most robotic control is accomplished with a high gain position control system. In this framework, a motion is designed for every task so that the robot can accomplish its motion by following the designed trajectory and an individual joint position command is calculated. A typical position controller with PD or PID control is implemented for each joint level controller and the joint position command is achieved by high gain feedback control.

As for the contact and motion control, in most cases, force sensor or contact sensor has been applied to measure the contact forces with the environment. And compliant contact can be realized by applying the stiffness or compliance gain in force control. This framework has been applied for manipulation and biped robots to minimize the impact force when the robot is walking or running. In this framework, stiffness of the contact need to be identified according to the environment, however, desired contact can be achieved relatively easily.

To realize more robust physical interaction with the environment, the robot needs to allow multiple contacts with the environment. However, in most cases, the position controller only account for the contact through the end-effector and the contacts through another link cannot be allowed. Moreover, the position controller cannot account for the dynamics of the system and is difficult to model the dynamics related with the contact in uniformed representation.

In this project, to realize interactive contact and whole-body control, the motion controller was reconstructed to control the robot by torque. To control the current position controlled humanoid robot by the torque command, Torque Transformer was applied. Because the controller of our robot was designed for the position control unit and is difficult to modify the control unit, the transformer was developed to convert desired joint torque command into instantaneous increments of joint position command or joint velocity command. The concept of the transformer was analyzed and validated on the position controlled robot.

On the basis of the torque control, dynamic effect of the humanoid robot was modeled by the Operational Space Formulation. The input torques for the system can be designed to accomplish the desired task as well as to compensate for dynamic effect of the contact with the environment. This provides the robot with higher performance in position tracking as well as in compliant motion. Therefore, advanced performance and complex behaviors can be implemented for robots if torque control is applied.

In this project, the motion controller was reconstructed by the Operational Space Formulation. By using this framework, we made progress towards the interactive multi-contact and control with the environment or with human, based on the following human-oriented approach.

(1) Compliant and passive whole-body control
(2) Interactive posture control
(3) Decoupled task control
(4) Multi-contact and force control
(5) Balance control.

Phase (1);

Compliant joint control on the current joint position controlled humanoid robot was realized by the Torque Transformer. It was applied to passive whole-body control, which enables passive contact with the environment.

Phase (2);
Based on the phase (1), compliant posture control and gravity torque control was realized. The posture control torque in the Operational Space Formulation was applied.

In phase (3);
Based on the phase (2), decoupled task dynamics by the Operational Space Formulation was realized. Precise position tracking at the end-effector was realized using the Torque Transformer. Multi-task control was also applied.

In phase (4);
Based on the phase (3), the Contact Jacobian was extended to deal with more general contact forces of the robot at any point on any link for any direction according to the desired contact situation. The Contact Jacobian is defined dynamically according to the designed contact and the estimated contact of the robot. That is, control point can be modified and the Contact Jacobian will be reconstructed on-line to respond to general contact and force control. In this framework, the null space control torque is used for motion control and is formulated so as not to affect the contact forces. The contact force can be modeled as direct control point or as redundant control point while controlling the end-effector.

To realize robust force control, AOB was used to the force control at the end-effector. All through this phase, precise and robust contact and force control was realized.

In phase (5);
The Torque Transformer and the Operational Space Formulation was applied to the upper-body control and the current balance controller was connected to realize stable balance control.

This framework was experimentally applied to the physical humanoid robot through *Torque Transformer*, which enables to command the current position and velocity controlled robot by the torque command. The results of the implementation which demonstrate the effectiveness of this approach will be presented.

BIOGRAPHY

1993: BS at Waseda University Mechanical Engineering
1995: MS at Waseda University Mechanical Engineering
1995-1997: Hitachi Co. Central Research Lab.
1997- :Fundamental Research Lab.

Humanoid robot Project at HONDA
<u>P3</u>
_Whole-body control for door opening
_Development of Human-like gesture motion (currently used by ASIMO)
_Development of dynamics simulator
<u>P4</u>
_Whole-body control for door opening
_Self-collision detection
_Manipulation with multi-finger hand
<u>ASIMO</u>
_Arm control
<u>Stanford</u>
_Operational Space Control for humanoid robot
_Dynamics and Control
_Torque control

Robust control strategies for locomotion and manipulation through compliance and force control

Jonas Buchli
in collaboration with
Mrinal Kalakrishnan, Michael Mistry, Peter Pastor,
Ludovic Righetti, Stefan Schaal, Freek Stulp,
and Evangelos Theodorou

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Traditionally robotics tasks are often solved using high gain position error feedback control (e.g. PID control). However, high gain position control has a severe disadvantage in that it relies critically on exact knowledge of the environment and exhibits suboptimal stiff behavior in case of external perturbations. In many cases high gain control can even lead to failure of the tasks (e.g. falling over in locomotion through difficult terrains), or damage to the robot or the environment (e.g. in grasping tasks). It becomes more and more clear that the natural way of how to address many robotic tasks involving contact with the environment is in force and torque space which naturally allows compliant control. Results show that such controllers can yield the robustness that is needed to get robots out of the lab and factory floors into unstructured environments [BKM+09]. The requirements and burden on the other elements of the overall robotic control system such as perception and planning are alleviated significantly.

However, there are a few major obstacles to overcome before such controllers will find widespread use. First, the hardware needs to support measuring and controlling forces and torques, not only in joints but also at end-effectors and other possible contact points of the robot. Furthermore, the community has less experience dealing with problems in the force domain or unstructured environments, both on the control and the planing level.

In this talk, I will focus on the control aspect of the problem. I will discuss both model based and model free approaches to circumvent the problems associated with high gain position control. I will include examples on floating base inverse dynamics and force control for robotic locomotion [BKM+09], reinforcement learning of impedance control, gain scheduling and force control for manipulation.

Many such controllers will require a model of the robot. One example is a rigid body dynamics model which allow to develop inverse dynamics controllers for low gain control. I will show how we appply our inverse dynamics methods for floating base systems [MBS10] to legged locomotion. The derived controller allows us to come closer to the goal of achieving compliant locomotion and relax the requirements on terrain knowledge and precision of end-effector position planning. Also, it allows for end-effector predictive force control while walking. To put our controller into context, I will present a short discussion of some of the control laws found in the literature and their relationships with our controller.

As an example of a model free approach, I will then show how we can obtain gain schedules that favor low impedance control but still ensure task achievement by reinforcement learning. To this end a new reinforcement learning algorithm (PI^2) is introduced. This algorithm is derived from first principles rooted in stochastic optimal control and path integrals [TBS10]. The same approach can be used also for learning policies for force controlled tasks such as writing on a whiteboard.

I will discuss the possible generalization and application of these methods to other robots such as humanoids and how to reconcile these application driven results with results from research in biological locomotion control. Last but not least, I will give an outlook how we can combine insight from research with different platforms to arrive with truly versatile and agile robotic locomotion platforms that perform well outside the lab in unstructured and stochastic environments.

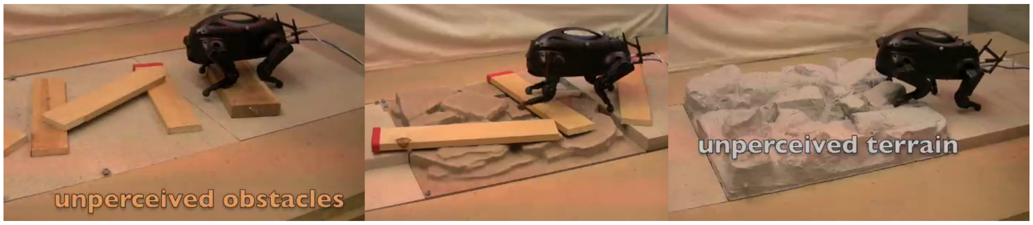

Figure 1: Setups to test the robustness of a quadruped locomotion controller towards non-perceived obstacles. The wooden obstacles are not perceived by the robot (see videos at [vid]).

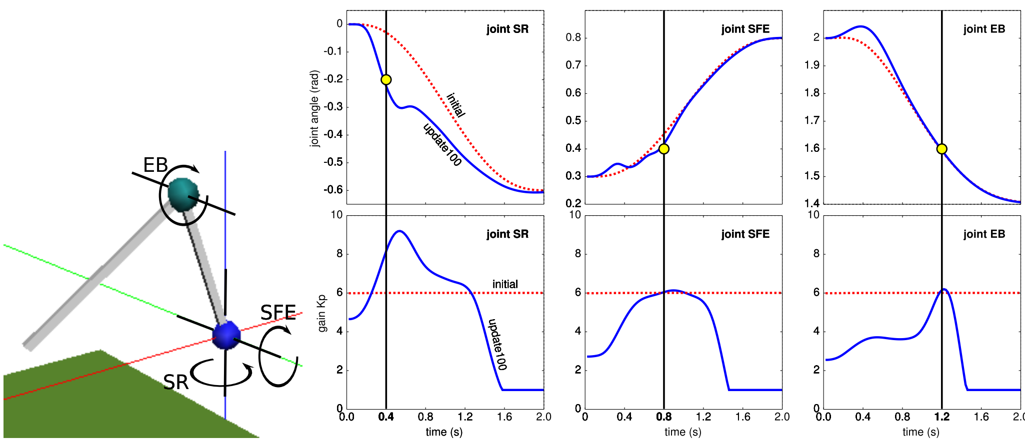

Figure 2: (left) 3-DOF Phantom simulation in SL. (right) Initial (red, dashed) and final (blue, solid) joint trajectories and gain scheduling for each of the three joints of the phantom robot. Yellow circles indicate intermediate subgoals.

References

[BKM+09] J. Buchli, M. Kalakrishnan, M. Mistry, P. Pastor, and S. Schaal. Compliant quadruped locomotion over rough terrain. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2009.

[MBS10] M. Mistry, J. Buchli, and S. Schaal. Inverse dynamics control of floating base systems using orthogonal decomposition. In *2010 IEEE International Conference on Robotics and Automation (ICRA2010)*, 2010. To appear.

[TBS10] E. Theodorou, J. Buchli, and S. Schaal. Reinforcement learning of motor skills in high dimensions: A path integral approach. In *2010 IEEE International Conference on Robotics and Automation (ICRA2010)*, 2010. To appear.

[vid] Videos and preprints available at `http://www-clmc.usc.edu`.

Jonas Buchli received a Diploma in Electrical Engineering from ETHZ (the Swiss Federal Institute of Technology, Zurich) in 2003 and a Doctorate from EPFL (the Swiss Federal Institute of Technology, Lausanne) in 2007. Since 2007, he is a postdoctoral fellow at the Computational Learning and Motor Control Lab at the University of Southern California. He has been involved in projects covering aspects of passive dynamic locomotion, planning and control for locomotion in rough terrains, compliance and force control, and reinforcement learning for high dimensional systems. His wider research interests include self-organization and emergent phenomena in complex systems, the theory of nonlinear dynamical systems. And, especially the possible applications of these topics to the intersecting field of engineering and biology.

Model-Based Control and Estimation of Humanoids via Orthogonal Decomposition of Rigid Body Dynamics

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I. Abstract

A humanoid robot that can coexist and work with humans in our own environment not only needs to be skillful and dexterous, but also compliant enough to be considered safe for human interaction. Robots controlled with traditional joint position control techniques typically require too high stiffness levels in order to maintain accuracy. Greater compliance can be achieved, without sacrificing accuracy, using *model-based* approaches such as inverse dynamics control. In these approaches, an estimated model of the robot's dynamics is used to proactively apply control forces required to track joint or task space trajectories.

Such model-based controllers have been well studied in the realm of manipulator robotics (see [1] for a recent review). However, humanoid and legged systems complicate matters since they are not fixed to their environments, and freely able to make and break new contacts. As a consequence, these *floating-base* systems have under-actuated dynamics with respect to an inertial reference frame, dynamically changing contact states, potentially closed loop kinematics, and contact forces that may not be known.

In this talk, I will present a relatively simple technique for full-body model-based control of humanoid robots. Using an orthogonal decomposition of rigid-body dynamics, we are able to express the complete inverse dynamics equations of the robot independently of contact forces [2]. We show how the technique can be used to cope with the under-actuation inherent in floating base systems and flexibly accommodate for changing constraints without the need to derive new analytical models for every new contact situation. Additionally, since the decomposition may only use kinematic variables, it avoids the pitfalls of relying on difficult-to-model dynamic projections.

In order in improve upon the accuracy of the rigid body models used for control, I will also present an approach for inertial parameter estimation of full body floating base humanoid systems [3]. While such data-driven estimation approaches typically require full force/torque sensing of all degrees-of-freedom, I will show how orthogonal decomposition allows us to use a limited force sensor set, while still obtaining a full-body estimation. For example, we may only require joint torque sensors when contact force measurement is unavailable or unreliable (e.g. due to slipping, rolling contacts, etc.).

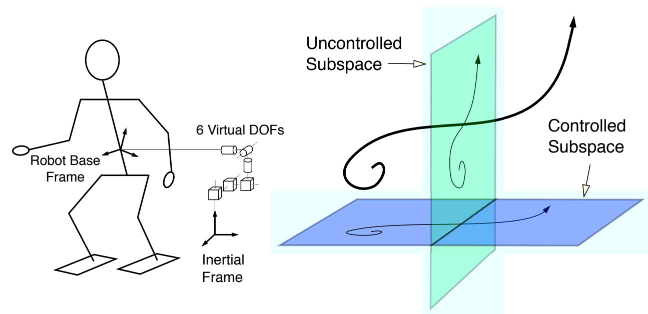

Fig. 1. Left: The floating base representation has 6 unactuated DOFs. Right: By using orthogonal projections, the system is divided into controlled and uncontrolled dynamics (e.g. the controlled subspace may not contain contact forces)

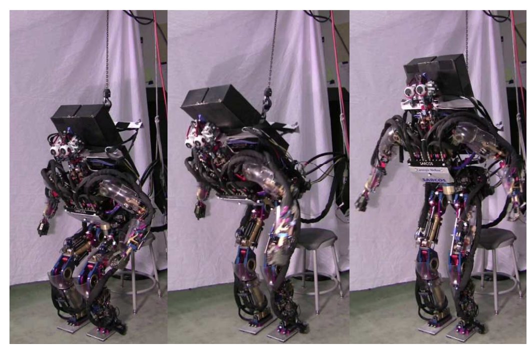

Fig. 2. Carnegie Mellon/Sarcos humanoid robot, standing up from a chair

Finally, I will also present some of our recent evaluations of our approaches on the Carnegie Mellon/Sarcos hydraulic force-controllable humanoid robot, engaging in dynamic tasks with contact state changes, such as standing up from a chair.

References

[1] J. Nakanishi, R. Cory, M. Mistry, J. Peters, and S. Schaal, "Operational space control: A theoretical and empirical comparison," *The International Journal of Robotics Research*, vol. 27, no. 6, pp. 737–757, Dec 2008.

[2] M. Mistry, J. Buchli, and S. Schaal, "Inverse dynamics control of floating base systems using orthogonal decomposition," *Proceedings of the 2010 IEEE Int. Conference on Robotics and Automation*, 2010.

[3] M. Mistry, S. Schaal, and K. Yamane, "Inertial parameter estimation of floating base humanoid systems using partial force sensing," *9th IEEE-RAS International Conference on Humanoid Robots*, 2009.

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Passivity-based force/torque control for hydraulic humanoid robots

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Abstract:

We will present a passivity-based force and torque control scheme employed in our hydraulic humanoid robots in two parts.

In the first part, starting from basic hydrostatic characteristics of hydraulic actuators, we show a simple proportional force feedback controller implemented in our SARCOS full-body humanoid robots [1] can control the actuator force (hence joint torque), but with the damping that depends on the force feedback gain. The resultant joint torque controller with damping is utilized for force and motion control in task (operational) space while suppressing the internal motions due to the joint redundancy. We will present this two-stage force control architecture in detail and show some performance analysis in the context of ground reaction force control tasks for our humanoid robots [2].

In the second part, we compare the above task-space force control scheme with a simpler, direct task-space force feedback control scheme from the viewpoint of the sensing and estimation errors [3].

Reference:

[1] Cheng, G., Hyon, S. Morimoto, J., Ude, A., Hale, J. G., Colvin, G., Scroggin, W. and Jacobsen, S. C., "CB: A humanoid research platform for exploring neuroscience," Advanced Robotics, vol.21, no.10, pp.1097-1114, 2007.

[2] Hyon, S., "Compliant terrain adaptation for biped humanoids without measuring ground surface and contact forces," IEEE Transactions on Robotics, vol.25, no.1, pp. 171-178, 2009.

[3] Hyon, S., "Momotor control strategy with virtual musculoskeletal systems for compliant anthropomorphic robots," IEEE/ASME Transactions on Mechatronics, vol.14, issue 6, pp.677-688, 2009.

Sang-Ho Hyon received the M.Sc. degree in Mechanical Engineering from Waseda University, Tokyo, Japan, in 1998, and the Ph.D. degree in Control Engineering from Tokyo Institute of Technology, Tokyo, Japan, in 2002.

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He has been engaged in developing various hydraulic and electronic robots performing dynamic balancing and locomotion.

His research interests include dynamical systems, nonlinear control theory, machine learning, and their application to humanoid, rehabilitation, and field robots.